Assessment Methodology Development for Proliferation Resistance and Physical Protection of Generation IV Systems

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Abstract One of the technology goals set for future Generation IV nuclear energy systems is to be "a very unattractive and least desirable route" for proliferation, and to provide increased physical protection against theft or sabotage. To evaluate system performance for this goal, an international Expert Group has been formed and has adopted an evaluation method that involves three elements: (1) a process to systematically identify the range of potential security challenges that could face the system—a "threat space" that includes State diversion or undeclared production of materials for nuclear explosives (proliferation resistance), and non-State theft or radiological sabotage (physical protection robustness); (2) methods for evaluating the system response to these challenges, at a level of detail appropriate to the stage of system or facility design; and (3) a set of measures of system performance that allow assessment and comparison of how well facilities systems meet the goal of providing a "very unattractive and least desirable route."

I. INTRODUCTION

A Roadmap for the development of advanced nuclear energy systems, known as Generation IV, was recently completed under the sponsorship of the U.S. Department of Energy's Office of Nuclear Energy, Science, and Technology (DOE-NE) and eight other countries under the Generation IV International Forum (GIF). The Generation IV Roadmap defines the following goal for proliferation resistance and physical protection (PR&PP) for future nuclear energy systems:

> *Generation IV nuclear energy systems will increase the assurance that they are a very unattractive and the least desirable route for diversion or theft of weapons-usable materials, and provide increased physical protection against acts of terrorism.*

DOE-NE and the NNSA Office of Nonproliferation and International Security (NA-241) have created an Expert Group to develop an assessment methodology for PR&PP. This Expert Group includes U.S. participants from national laboratories (ANL, BNL, INEEL, LANL, LLNL, SNL), academia, international experts from five additional GIF member countries (Canada, France, Japan, Republic of Korea, and the United Kingdom), the International Atomic Energy Agency, and observers from the U.S. State Department and the U.S. Nuclear Regulatory Commission.

The work of the Expert Group builds upon the recommendations of two recent activities:

- Guidance provided in the Generation IV Roadmap regarding future system evaluations [1], and
- Guidelines for the Performance of Nonproliferation Assessments, recently issued by NA-241 [2].

The Expert group has agreed on the definition of proliferation resistance and physical protection as follows:

> ***Proliferation resistance*** is those characteristics of a nuclear energy system that impede the diversion or undeclared production of nuclear material, or misuse of technology, by States in order to acquire nuclear weapons or other nuclear explosive devices.
>
> ***Physical protection*** is those characteristics of a nuclear energy system that impede the theft of materials suitable for nuclear explosives or radiation dispersal devices, and the sabotage of facilities and transportation, by sub-national entities.

Based on these definitions and the above definition of the Generation IV PR&PP Technology Goal, the proliferation resistance goal is to be the least desirable route to proliferation by virtue of enhanced intrinsic technical features intended to prevent or hinder the misuse of the nuclear system and its technology in the production of nuclear weapons or other nuclear explosive devices. Similarly, the physical protection goal is to be the least desirable route to theft of materials suitable for nuclear explosives or radiation dispersal devices and to sabotage of facilities and transportation.

The PR&PP evaluation methodology is structured around three elements, illustrated in Figure 1. As shown in Fig. 1, the PR&PP evaluation methodology first identifies the range of potential threats that could challenge the security of Generation IV facilities and systems. For PR, threats span the range of strategies that States might pursue to obtain material for use in nuclear explosives. For PP, threats span approaches to theft of materials, and to radiological sabotage. From this comprehensive threat space, the method selects a representative subset of the threats for evaluation. In the initial phase of assessment, during the early stages of design, this involves qualitative specification of the different types of threats to be considered in evaluation. In the semi-quantitative and quantitative phases of assessment, this involves the identification and specification of a representative set of specific challenges, from the broader threat space, at a level of detail sufficient to support analysis and comparison of the response of different systems. The phased approach is needed because, at the current conceptual design stage of Generation IV, the systems are specified at only a high, functional level, there is no operational information that directly pertains, and the institutional context for systems evaluation is broad and evolving. As specific information is developed in these areas, the evaluation methodology can be applied in a commensurate way to assess the degree of proliferation resistance and physical protection that is being achieved.

The methodology (Fig. 1) then applies a phased evaluation approach to analyze system response, and to evaluate metrics and measures for the outcomes of the system response. Six high-level measures have been identified for PR and six for PP. Each measure represents a major characteristic of the system response that would be an important impediment to the strategy of a proliferant State (PR), or of a non-State group attempting theft or sabotage (PP). For example, one PR measure is "proliferation time," the minimum time required to overcome the multiple barriers to acquisition of the first significant quantity of fissile material. An example of a PP measure is "adversary delay," the time required to overcome intrinsic barriers to access and disable a vital equipment target set (radiological sabotage), or to remove materials (theft). Combined together, the complete set of measures provides information for program policy makers and system designers to compare specific system design features and integral system characteristics and to make choices among alternative options. This phased evaluation approach allows assessments to become more detailed and more representative as system design progresses.

This paper summarizes the framework for the proliferation resistance methodology, describes the threat space considered, provides an overview of the methods under consideration to evaluate the system response, and the proposed measures used to represent proliferation resistance and physical protection robustness.

CHALLENGES →	SYSTEM RESPONSE →	OUTCOMES
Threats	*PR & PP*	*Measures & Metrics*

Figure 1. Framework for PR&PP assessment

II. THREAT SPACE DEFINITION

The first element of a PR&PP evaluation is the definition of the threat space to be considered. Because PR&PP evaluations are required to specify and report what types of threats have been considered, PR&PP evaluations can be reviewed for the completeness of the threat space considered.

The proliferation-resistance threat space, for State acquisition of materials for nuclear weapons, has four principal dimensions: motivations, aspirations, capabilities, and strategies. Motivations define the urgency of the proliferation activity, the number and characteristics of weapons sought, and the resources to be employed and levels of risk to be taken. Aspirations define the type, size, and rate of production of weapons sought. The capabilities define the resources—technical skills, general economic and manpower resources, indigenous natural resources, and industrial and nuclear capabilities—available in the state. Strategies define the broad categories of approaches to proliferation, ranging from construction of a fully clandestine production system or clandestine replication of declared facilities, to diversion of materials from declared inventories, to undeclared production in declared facilities, to abrogation.

The physical-protection threat space, which is focused upon the subnational threats of theft and radiological sabotage, has five principal dimensions: class of adversary, aspirations, capabilities, tactics, and modes of attack. The categories of classes of adversaries include outsiders, insiders, and combinations of outsiders and insiders. Aspirations relate to the specific goals of the adversaries, ranging from disruptions of normal operations to theft of materials to the generation of radiological releases. Capabilities span a range of skills, resources, and levels of dedication that could be available to adversaries. Tactics include stealth, deceit, and overt force alone or in combination. Modes of attack range from ground assault to standoff to cyber.

The level of detail in the definition of the threats to be considered in an assessment must be appropriate to the level of detail in the assessment. In the phased approach of PR&PP assessment, level of detail ranges from qualitative to semi-quantitative to quantitative. The specific threat definitions used in the evaluation should always be reported along with the evaluation results. Some studies may focus on a subset of the threat space to enable more detailed analysis; in this case the subset of threats should be clearly defined.

III. PR&PP METRICS AND MEASURES

The goal for Generation IV systems is to provide "a very unattractive and least desirable route" for proliferation, and to provide increased physical protection against theft or sabotage.

With input from a detailed review of previous studies of proliferation resistance (PR) and physical protection (PP), the PR&PP Expert Group has recommended a set of high-level measures for proliferation resistance and physical protection robustness for the evaluation of Generation IV nuclear energy systems. The recommended set of top-level measures, six for PR and six for PP, provide the basis for comprehensive PR&PP assessments for a spectrum of threat scenarios, representing the "threat space." These top-level PR&PP measures in turn depend upon intermediate and lower level metrics. The lower level metrics can represent a variety of elements, ranging from intangible qualities to specific characteristics of a process, facility or material that can be described in terms of physical parameters.

Six PR measures (indices) have been defined: proliferation technical difficulty, proliferation resources, proliferation time, fissile material quality and quantity, detection time, and detection resources. .

Likewise, six PP measures (indices) have also been defined: operational accessibility, adversary delay, consequences and mitigation potential, detection time, interruption time, and physical protection resources.

The measures for PR reflect the most important quantities that the proliferator considers in comparing proliferation strategies. In a similar way, measures for PP reflect the quantities that a non-State actor considers in comparing strategies for theft or sabotage.

The Experts Group has deferred finalizing the detailed definitions of the PR&PP measures, until the measures have been proven to be tractable to evaluate in an initial application study. Here it is recognized that different PR&PP threats can have the potential for success for substantially different reasons, and thus different measures may dominate for different threats.

As an example, in a proliferation strategy that diverts small quantities of plutonium-bearing material, below detection thresholds, the ability to purify the material in a simple laboratory-scale facility reduces the importance of the materials quality measure. For this clandestine diversion strategy, detection time creates the most important issue for the proliferator, and the detection time measure dominates the evaluation. Conversely, for a strategy of abrogation and rapid processing of large quantities of plutonium-bearing material, before effective international response can occur, the material quality measure dominates.

The proposed high level measures for PR and PP have been selected to represent the integrated set of delays inherent in a nuclear system against diversion, undeclared production, theft and sabotage, as well as the timeliness of detection of such activities. Examination of the high level measures clearly indicates that they can be broken down into multiple other elements. The evaluation of these measures by decomposing them into elements that can be related more directly to the system features and physical characteristics should be commensurate with design information.

Moreover, relating the proposed high level measures to the physical characteristics and features of the systems will provided the basis for (1) comparing systems on the basis of PR and PP, and (2) identifying weaknesses or strengths of the systems that can provide feedback to the development process.

The question of independence of the high level measures is often raised among practitioners of methodologies of PR&PP. There is a concern that a decision maker should be provided with information that is not ambiguous and might be presented in terms of redundant factors. Moreover, depending upon the method selected for the assessment, the analysis can be performed efficaciously if there is a notion of independence among the measures. Recognizing the dependencies among the top level measures, the challenge for the analyst is to construct the measures avoiding overlapping attributes in the construction of subordinate metrics for each measure.

It is also important to include a measure of sensititivity and uncertainty in all the assessments for PR and PP. In both qualitative and quantitative assessments, the metrics and the high level measures represent estimates obtained with incomplete knowledge. The sensitivity of key results to reasonable alternative assumptions of the analysis should be displayed wherever the impact of on the outcomes is deemed to be significant. To the extent that alternative assumptions can be judged to be of relative significance, the impact on final results should be reflected as uncertainties. Whether the results are obtained with expert judgment or with detailed models, they must be reported with a measure of their uncertainty. Further, the presentation of results that reflect the sensitivity and uncertainty must be characterized and displayed in a form that is understandable by the users.

IV. EVALUATION OF SYSTEM RESPONSE

Several methodologies have been considered for use in nonproliferation assessments.[1,2] The most promising approaches include scenario-based methods,[3] such as probabilistic risk assessment methods to quantify material diversion pathways, and attribute-based methods,[4] which aim at identifying and quantifying material diversion barriers. Other methods, such as two-sided approaches (wargaming) and dynamic modeling have also been identified[1,2] as potentially useful in specific nonproliferation assessment applications. Because Generation IV focuses on integrated nuclear energy systems, system-level models will be necessary in addition to facility-level models, to integrate the effects of technology options over time-varying inventories of materials to be processed and managed.

A phased evaluation approach to quantifying measures and assessing nuclear systems for their PR&PP is recommended. As discussed above, this phased evaluation approach will allow the assessments to become more detailed and more representative as the designs progress. This will provide important information and feedback to designers and evaluators during the viability and performance phases of Generation IV -- from the stage of basic process selection, to the detailed layout of equipment and structures, to facility demonstration testing.

In the phased approach, qualitative assessments are used to provide preliminary results and guidance and semi-quantitative assessments provide increased specificity to designers and policy makers as the concepts evolve. These assessments range from direct qualitative evaluation of high level measures based on expert judgment to more structured, semi-quantitative attribute assessments such as the barrier analysis, simple rating methods, or pair-wise comparison (analytical hierarchy process). The phased approach is depicted in Figure 2. Thus three basic levels of detail are anticipated:

Level 1. Qualitative assessment based on structured support, such as checklists, barrier analysis, and expert judgment can be performed, even when design information and operational experience are sparse. By considering a representative set of qualitative threat descriptions, the full range of important qualitative system features can be identified. For example, for the threat of State diversion of material at low rates, the feature of an effective international safeguards system capable of detecting sufficiently low quantities would be considered. The evaluation can ensure that these qualitative system features are identified and considered in design. Because the qualitative system features are related to specific types of threats, the analyst can alert the decision maker to which threats that may emerge as being "credible" in generating undesirable outcomes. Likewise, expert judgment can be used to identify threats which are highly unlikely to result in an undesirable outcome, that is, those specific ways in which the system is particularly robust. Later cases become more analytical and quantitative, but the basic principles of these qualitative criteria continue to apply.

Level 2. Semi-quantitative evaluation. Analysts begin to add structure and integral evaluation techniques to the assessment. An understanding of the consequences to be modeled later in the full probabilistic risk assessment is required for effectiveness. The potential consequences (e.g., the nature of the adversary aspirations that might be achieved, and likelihood of adversary success prior to detection and effective intervention) are ranked in a conservative manner to lend some sense of priority to the scenarios, but, lacking full event sequence development, cannot be taken literally. As even more information is developed, the analysts can apply formal search processes to identify and rank threats and to build functional scenarios. The design needs to have progressed to the point that the intrinsic and extrinsic characteristics and systems capable of providing key PR or PP functions have been defined. Such scenarios can be developed in many forms (flow charts, narrative descriptions, event trees, etc., or the results of simulation). The important thing at this level is that they be complete – as close as possible to the scenarios that would be analyzed in a full quantitative assessment.

Level 3. Full quantitative assessment. The design must be sufficiently developed to identify component characteristics, points of possible (not just planned) human interaction, safeguards protocols, procedures and training, physical mechanisms that apply (supported by mechanistic calculations and experiments (physics, chemistry, etc.)). Even when full data are not available, there must be enough information available to support expert elicitation. For PR&PP assessments, there will always be a large element of uncertainty with regard to threat characterization, even at the Level 3 stage. The best form of the scenario structuring (event tree/fault tree models, simulation models, etc.), mechanistic analyses, and evaluation of likelihood will depend on the scenarios themselves, the state of design information, and the quality and applicability of available information. In addition to the methods introduced earlier, the framework must address data sources and data analysis needs

In terms of selection of specific evaluation methods in the progressive evolution from the basic qualitative level 1 to quantification in levels 2 and 3, the first, semi-quantitative, steps could focus on attribute methods and provide increased formalism in value assigned to each attribute. Next would come development of scenarios and finally quantification of those scenarios. Attribute approaches would first apply weighting schemes in the form of value functions or utility functions. Some have argued that such preference functions need to be "rolled up" to provide an overall score for each case. At low level of detail, use of roll ups does not seem appropriate, primarily because there is no clear link to integrated importance.

The next step would be development of functional scenarios. Analysts would first sketch "functional" successes/failures that can emanate from each threat. They could also screen sequences that do not lead to significant consequences. The remaining scenarios would be examined to determine if there exist technical knowledge gaps important to the scenarios.

At the level 1 or 2 of detail, it may be reasonable to make an early application of wargaming. The NPAM guidelines document[1,2] discussed the relevance and applicability of wargaming[5] to nonproliferation scenarios as a tool for assessment. A wargame would be a role-playing exercise where human participants make sequential decisions that determine the unfolding of a scenario. Models, simulations, lookup tables or human umpires can be used to determine the consequences of the decisions and to advance game time. In the early Generation IV designs, when system viability decisions are being made, details of systems and their attributes may not be known with any fidelity. A wargame in which experts playing adversaries evaluate unexamined paths to proliferation might develop insights that could be helpful to designers.

Quantification can begin at any stage of the analysis. At first quantification is based on expert elicitation. When this is the case, care is required to ensure that bias is controlled and uncertainty is thoroughly represented. With increasing availability of design and operational information, more detailed modeling can be performed. As technical knowledge increases through analysis and experimental results, less reliance on expert elicitation is required.

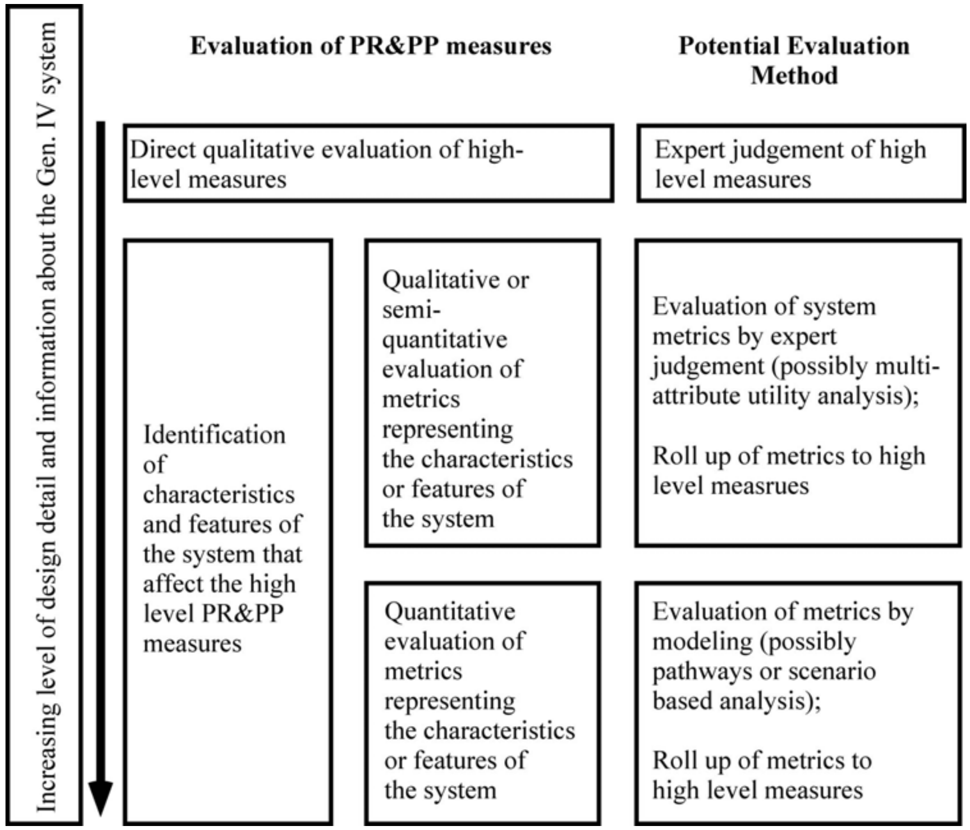

Figure 2. Phased evaluation approach for PR&PP assessments

V. CONCLUSIONS

This paper presents initial ideas on the proposed PR&PP assessment framework. The framework provides the outline of the overall evaluation methodology in terms of its scope and major elements. It defines an approach for specifying the threat space—the potential range of national or sub-national aspirations, capabilities, and strategies that might challenge Generation IV systems—to be used for PR and PP evaluation. It identifies six high level measures for PR and six for PP.

The phased framework maximizes early, useful feedback to designers and evaluators during the viability and performance phases of Generation IV research and development -- from the stage of basic process selection, to the detailed layout of equipment and structures, to facility demonstration testing.

Key elements of the implementation still need to be completed. In particular, the process of specifying the threat space, or representative points in the threat space, must be established. It is desirable to focus, to the extent possible, on those elements that are particular to the Generation IV systems, and where not possible to use to provide reasonable assumptions about the external, institutional context. At the same time, an approach to completeness is also needed to attain confidence that the important scenarios and pathways to proliferation or system physical disruption are included and that the uncertainties are understandable . The aggregation of the different system elements into the assessment summary is another procedure step that is being developed.

The development of the measures, threat space, and methodology framework is a work in progress. It is expected to evolve as a result of iterations within the Expert Group and from demonstration that the measures can be evaluated in a phased manner, with a level of effort appropriate to the system design level, and that the resulting measures provide useful and actionable information for the key Generation IV stakeholders. An application will be performed with a sample problem to demonstrate and further improve the methodology.

ACKNOWLEDGEMENTS

This work was performed for the NA-241 Division of the U. S. National Nuclear Security Administration and the U.S. Department of Energy, Office of Nuclear Energy Science and Technology. We acknowledge the contributions of all of our collaborators and program managers.

REFERENCES

1. US DOE Nuclear Energy Research Advisory Committee and the Generation IV International Forum, *A Technology Roadmap for Generation IV Nuclear Energy Systems,* GIF002-00, December 2002.

2. R. DENNING et al., *Guidelines for the Performance of Nonproliferation Assessments,* Transactions of the American Nuclear Society, **87**, 365-366, Washington DC, November 17-19, 2002.

3. ROCHAU, G. E. et al, “Risk-Informed Proliferation Analysis,” Sandia National Laboratories Report, SAND2001-2020, June, 2002.

4. NERAC, TOPS TASK FORCE, “Annex: Attributes of Proliferation Resistance for Civilian Nuclear Power Systems,” USDOE, October 2000. Available at: http://www.nuclear.gov/nerac/FinalTOPSRptAnnex.pdf

5. PERLA, P, “The Art of Wargaming”, Naval Institute Press, 1990.